Team Reports: NASA Goddard Space Flight Center

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Executive Summary
Principal Investigator: Michael Mumma

The central goal of the Goddard Center for Astrobiology is to understand how organic compounds are created, destroyed, and altered, during stellar evolution leading up to the origin of life on a planet, such as Earth. Planetary systems form by collapse of dense interstellar cloud cores. Some stages in this evolution can be directly observed when stellar nurseries are imaged, while other stages remain cloaked behind an impenetrable veil of dust and gas. Yet to understand the origin of life on Earth, we must first develop a comprehensive understanding of the formation of our own planetary system. To understand the probability of finding life elsewhere we must understand both the similarities and differences between the evolution of our own system and that of a typical star.

Dense cloud cores are very cold (10–50K); their dust grains are coated with ices comprised of water and organic compounds. Many of these organics have potential relevance to the origin or early evolution of life, if delivered to planets. The survival of these organics through the violent birth–phase of a star is less certain. Properties of the young star (its mass, spectral energy distribution, whether it formed in isolation or as a multiple star, etc.) help control the evolution of organic material in the proto–planetary disk. The location within the disk is important since the nature and effectiveness of such processing depends strongly on distance from the young star, on distance above the nebular mid–plane, and on time. The ultimate delivery of these primitive organics to young planets and their moons also evolves with time, as the bodies grow in size and as the nebula clears.

We seek to better understand the organic compounds generated and destroyed in the interstellar and proto–planetary environments, through observational, theoretical, and laboratory work. We have begun to examine the potential for and limitations to delivery of exogenous pre–biotic organics to planets, examining factors that enhance or restrict this potential. To follow these factors over time, from the natal cloud core through the end of the late heavy bombardment (~ 4.1 Ga) and evaluate the possible role of exogenous organic material in terrestrial biogenesis, we have divided the research into four themes as well as our education and public outreach program. These themes are:

Theme 1: *Establish the taxonomy of icy planetesimals and asteroids to evaluate their potential for delivering pre−biotic organics and water to the young Earth and other planets.*

Theme 2: *Investigate processes affecting the origin and evolution of organics in planetary systems.*

Theme 3: *Conduct laboratory simulations of processes that likely affected the chemistry of material in natal interstellar cloud cores and in proto−planetary disks.*

Theme 4: *Develop advanced methods for the in−situ analysis of complex organics in small bodies in the Solar System.*

This first year of our NAI participation saw major emphasis on infrastructure: recruiting students, staff, and permanent employees, updating computational facilities, building laboratories, and furnishing them with equipment. In addition to the five undergraduate students recruited through our summer internship program, we recruited two additional undergraduates and two high school students for part−time work. Beyond this we recruited a graduate student, three post−doctoral researchers, two senior soft money scientists, and hired one civil servant as a result of establishing the Goddard Center for Astrobiology.

Besides positioning ourselves for research activities next year with staff and equipment, and participating in numerous meetings and workshops, we secured time on telescopes for the observation of comets (on the NASA Infrared Telescope Facility (IRTF), the Keck Observatory, and the Five College Radio Astronomy Observatory) and young stellar objects (on the Very Large Array).

In addition to planting these seeds for the future, each of the four themes has made progress in our scientific goals. An important laboratory goal of Theme 1 is to fingerprint late additions to the Moon using the relative abundances of the highly−siderophile elements that occur in high abundance in likely impactors, but extremely low abundance in the indigenous lunar crust. The initial work has consisted of selecting and separating pure melt rock from lunar highlands breccias. 2g of two Apollo 17 breccias (Figure 1) were obtained from the Johnson Space Center curatorial facilities; we have cleanly separated 13 chips from one and 6 chips from the other to measure Os isotopes and other highly siderophile element abundances. Final checks on the chemical blanks for the separation and measurement procedures are being completed. The analytical work; powdering, dissolving, separating elements of interest, and mass spectrometric measurements, start in July, 2004.

Figure 1. Apollo 17 lunar melt rocks have been selected and are ready for analysis of highly siderophile element abundances and osmium isotopic compositions.

A second objective in Theme 1, establishing the taxonomy of icy planetesimals, has also made progress with the measurement of CO, CH_4 , and other volatile organic constituents at high spectral resolution in three comets; one short−period, Jupiter Family Comet (JFC) (2P/Encke) and two long−period, Oort Cloud comets (C/2001 Q4 NEAT and C/2002 T7 LINEAR). In particular, spectra of Comet 2P/Encke were obtained at high spatial and spectral resolution about the nucleus; rotational temperatures of coma gases were between 25 to 30K, methane was severely depleted while the relative abundances of ethane, methanol, hydrogen cyanide, and acetylene in this JFC agreed with those of “typical” Oort Cloud comets.

A vital component of Theme 2 is the observation of proto−planetary disks (proplyds); (near−infrared single−slit cross−dispersed echelle and grating spectrometer (NIRSPEC) operating at the Nasmyth focus on Keck II Observatory, HI) spectra of the proplyd HST 10 in Orion are being processed Using the Very Large Array we have detected the first three carbon sugar (dihydroxyacetone) in star− (and planet−) forming molecular clouds. This detection highlights the role of prebiotic chemistry long before planetary surfaces are amenable to the synthesis of such compounds, and suggests that the chemistry leading to life is widespread throughout the universe. Theme 2 investigators are measuring infrared flux and spectrum of the transiting extrasolar planet HD 209458b and are also using ground−based data to measure the infrared spectrum of the planet from 2 to 5 microns, using a similar technique.

Theme 3 is entirely focused on laboratory work. One aspect simulates the vacuum and low–temperature environment of space using a high vacuum chamber and a cryostat. Ice samples condensed on a cooled mirror inside the cryostat are irradiated with 1 MeV protons to simulate cosmic–ray bombardment or are photolyzed to simulate vacuum–ultraviolet (UV) exposure. Motivated by detections of nitriles in Titan's atmosphere, cometary comae, and the interstellar medium, we completed laboratory investigations of the low temperature chemistry of acetonitrile, propionitrile, acrylonitrile, cyanoacetylene, and cyanogen (CH_3 CN, CH_3 CH_2 CN, CH_2 CHCN, HCCCN, and NCCN, respectively). Trends were sought, and found, in the photo– and radiation chemical products of these molecules at 12 – 25K. In the absence of water, all of these molecules isomerized to isonitriles, and CH_3 CN, CH_3 CH_2 CN, and (CH_3) 2 CHCN also formed ketenimines. In the presence of H_2O, no isonitriles were detected but rather the isocyante ion (OCN^-) was seen in all cases. Although isonitriles, ketenimines, and OCN^- were the main focus of this work, we also examined cases of hydrogen loss, to make smaller nitriles, and hydrogen addition (reduction), to make larger nitriles. HCN formation was seen in most experiments. These results are directly applicable to the nitrile ice chemistry on Titan, in cometary ice, and in the interstellar medium.

Members of Theme 3 have synthesized autofluorescent membranes (Figure 2), and possibly even vesicles, from a realistic interstellar ice mixture (H_2O, CH_3 OH, NH_3, and CO at 15 K) using the same experimental equipment discussed above. The properties of these membranes are being characterized by collaborator D. Deamer (University of California, Santa Cruz).

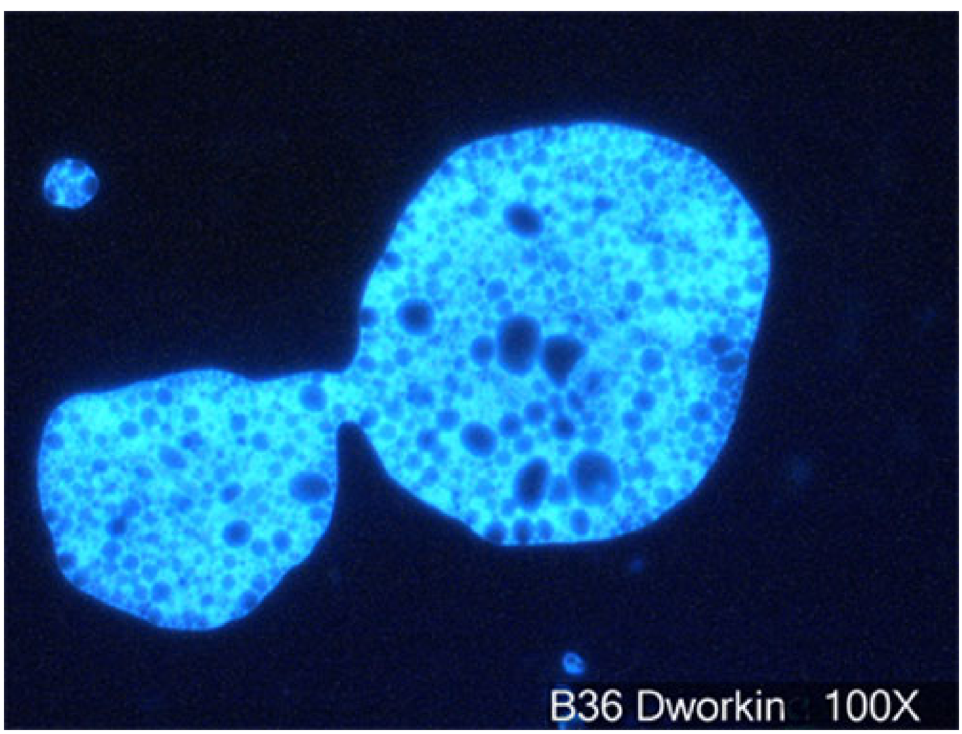

Figure 2. Micrograph of fluorescent membranous material generated by proton irradiation of a realistic interstellar ice dispersed in pH 8.8 10 mM phosphate buffer shown under oil–immersion microscopy at 1000x.

Members of Theme 3 have developed computer codes for chemical kinetic calculations in the solar nebula as a function of temperature, pressure, and mixing rate (parameterized as an eddy diffusion coefficient). Experimental studies of the efficiency of different types of catalysts for conversion of $CO + H_2$ to CH_4 have been completed. We have also observed that the carbonaceous coating deposited onto the surfaces of amorphous iron silicate and magnesium silicate grains during the surface−mediated conversion of CO, N_2 and H_2 into more complex hydrocarbons (previously believed to "poison" such grain catalysts) also reacts with CO, N_2 and H_2 to form complex organic products. These results imply that, to some degree, nearly all solid materials in the primitive solar nebula could serve as substrates to convert CO, N_2 and H_2 into organic materials.

The development of instruments for organic analysis on space missions is the crux of Theme 4. To prepare for flyby, rendezvous, and sample return missions to comets, the development of advanced organic analysis techniques has been initiated. These techniques include: laser desorption mass spectrometry; pyrolysis mass spectrometry; and the solvent extraction of organic molecules followed by chemical derivatization. In the initial stages of this work a variety of Mars analog materials such as Atacama desert soils, Hawaiian basalts, meteoritic sample s, and solid material generated by some of the nitrile irradiations conducted by Theme 3 have been used to cross compare these techniques. Some of these materials also serve as cometary analogs and the chemistries developed for their analysis may be relevant for future cometary research.

Initial analyses of carbonaceous chondrites and simple carbon−matrix standards with laser desorption methods have contributed to a developing database of refractory macromolecular materials that may be present in comets and other small bodies. This database should lead to increased understanding of (i) parent body synthesis and processing; (ii) impact survival of more fragile incorporated compounds; and (iii) enhanced in situ protocols for determining the full breadth of cometary organics.

Finally, our team has made great progress in our education and public outreach endeavors. In the Spring and Summer of 2004 educational efforts of the Goddard Center for Astrobiology included the implementation of a pilot program called the 2004 Summer Undergraduate Internship in Astrobiology (SUGIA), the initiation of a high school curriculum development project with the Minority Institution Astrobiology Collaborative (MIAC) and the modification of an undergraduate Astronomy course at the University of Maryland College Park (UMCP) to focus on Life in the Universe. In addition, we are working with MIAC to systematically observe comets through emission−line filters at optical wavelengths. This effort is led by Dr. Donald Walter (South Carolina State University), and will utilize telescopes in Arizona. Imaging studies on the Kitt Peak 1.3−m telescope are in the science−testing phase, and should be completed by the end of 2004. Monitoring of comet 9P/Tempel 1 is planned for spring/summer, 2005 to support the Deep Impact mission. Dr. Walter is in residence at GSFC in summer, 2004, through our Summer Faculty Fellowship Program, working closely with Co−I DiSanti on aspects of our database of cometary IR spectra.

Figure 3. The Astrobiology in Secondary Classrooms Curriculum Development team poses for a picture on the last day of their stay at the Goddard Center for Astrobiology, July 2, 2004. Pictured are: (back row) Dr. Michael J. Mumma, Director of the GCA; Kevin Jones, Branchville High School, SC; Michael Cherry, Hillside High School, NC; Jim Poland, Seneca High School, SC; Dr. Leroy Salary, Professor, Norfolk State University; Dr. Michael DiSanti, Co−Investigator, GCA; (front row) Brooke L. Carter, Research Operations Coordinator, GCA; Dr. Donald Walter, Professor, South Carolina State University; Dr. Jennifer Stewart−Wright, Professor, Tennessee State University; Dr. Jason Dworkin, Co−Investigator, GCA; Laurette Cousineau, Williamson County Schools/Brentwood High School, TN; Dr. Nasrollah Hamidi, Visiting Professor, South Carolina State University; Judy Butler, CEO, Dragonfly Enterprises; Stephanie Stockman, E/PO Lead, GCA (not pictured).